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Anisotropy in the haptic perception of force direction and magnitude

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Abstract—Although force-feedback devices are already being used, the human ability to perceive forces has not been documented thoroughly. The haptic perception of force direction and magnitude has mostly been studied in discrimination tasks in the direction of gravity. In our study, the influence of physical force direction on haptic perception of force magnitude and direction was studied in the horizontal plane. Subjects estimated the direction and magnitude of a force exerted on their stationary hand. A significant anisotropy in perception of force magnitude and direction was found. Force direction data showed significant subject-dependent distortions at various physical directions. Normalized force magnitude data showed a consistent elliptical pattern, with its minor axis pointing roughly from the subject's hand to his/her shoulder. This pattern could be related to arm stiffness or manipulability patterns, which are also ellipse-shaped. These ellipses have an orientation consistent with the distortion measured in our study. So, forces in the direction of highest stiffness and lowest manipulability are perceived as being smaller. It therefore seems that humans possess a 'sense of effort' rather than a 'sense of force', which may be more useful in everyday life. These results could be useful in the design of haptic devices.

Index Terms—Force direction, force magnitude, human perception, anisotropy, arm mechanics, psychophysics.

1 INTRODUCTION

THE application of haptic devices in tele-operation systems is increasing, but the presented force feedback does not always feel intuitive [1], [2]. So, to improve this, it would be useful to know more about the human perception of force. The perception of weight was the first subject investigated in haptic research, described in Weber's classic work on haptic weight perception [3]. When the development of haptic devices began, research changed from looking only at force perception in the direction of gravity [4], [5], [6] to looking at it in three dimensions (e.g. [7], [8], [9], [10]). This also changed the term 'weight perception' to 'force perception'. Both aspects of force, direction and magnitude, have mainly been investigated in discrimination experiments, focusing on the precision of force perception. The aim of our study was to investigate the relation between physical and perceived forces at different force directions and magnitudes, in order to obtain more insight into what humans are actually perceiving rather than with which precision they are perceiving it. The next section provides a summary of the literature on perception of force magnitude and direction.

The discrimination of **force magnitude** in the direction of gravity is a thoroughly investigated subject (for a review of force and weight perception, see [11]). An important parameter in discrimination experiments is the Weber fraction, which refers to the minimum percentage of stimulus difference that is perceivable and describes the *precision of force magnitude perception*. Typically, Weber fractions range from 8% [12] to 13% [13] for force magnitude discrimination tasks in the direction of gravity. In contrast to this large body of studies, magnitude discrimination experiments in other directions are still scarce. A start was made by establishing discrimination thresholds for forces exerted on a stylus, using several direction-magnitude combinations in the fronto-parallel plane [7]. A significant anisotropy was found, as Weber fractions were about 10% in the upward, and 22% in the lateral direction. The diagonally right-up direction showed the highest Weber fraction of 30%. Unfortunately, the stimuli were forces that varied in direction and magnitude of force simultaneously, which makes it impossible to distinguish between the two. A similar method was used in another study [8], which tested force magnitude discrimination by providing forces while subjects were moving the stylus of a haptic device. They found a higher Weber fraction for forces at a 45° angle with the movement direction, compared to directions parallel and perpendicular to the movement. Together, these studies seem to suggest discrimination is poorer at some non-cardinal directions, with respect to the orientation of the hand, than at cardinal directions.

In addition to these studies, some more elaborate work on discrimination of force magnitude at cardinal directions has been done. Dorjgotov et al. [9] found a mean Weber fraction of 13% for forces exerted along all three cardinal axes. No discrimination difference between the axes was found. A similar result was found using a range of force magnitudes in a discrimination task where subjects were holding a handle of a haptic device (Weber fraction: 15%) [10]. So, for the cardinal directions the mean Weber fraction for force magnitude seems to be

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13–15%.

Another parameter that can be investigated using discrimination experiments is the difference between force magnitude perception at different directions. This parameter, anisotropy, has been studied in only one experiment [9]. Subjects were asked to discriminate between a reference force, exerted along the dorso-ventral axis towards themselves, and a test force exerted on one of the cardinal axes, using a haptic device held with the whole hand. They perceived the magnitude of forces along the dorso-ventral axis towards themselves as larger than forces exerted in any other cardinal direction. There was no difference between the other directions tested.

A more direct way to investigate anisotropy is by studying the *relation between physical and perceived magnitude* through force magnitude estimation experiments. This would allow a comparison of force magnitude perception in various directions at various force levels. Only one study has investigated this, showing an anisotropy in force magnitude perception at different force directions [14]. However, they used a force range between 5 and 30 N, which are quite large forces when controlling a master device for a long time. The importance of stimulus direction for its perceived intensity has been hinted on by Dorjgotov et al. [9]. This effect has also been established in other haptic studies. For instance, the radial-tangential illusion is not only a well-known visual illusion, but also a haptic illusion of distance [15]. Subjects overestimate a distance that is presented radially, compared to a distance that is presented tangentially. As this is a very consistent effect, force magnitude perception could also be subject to such distortions.

The discrimination of **force direction** has also been studied in some experiments [16], [17]. In these, force direction discrimination tasks were performed to establish the *precision of perception of force direction* by exerting a force in the fronto-parallel plane on the passive index finger. This research was extended by using the same paradigm to test force direction perception of the index finger during active movement of the arm [18]. In all three studies, a JND (Just Noticeable Difference: the smallest absolute difference that is perceivable) of about 30° was found that did not differ significantly between reference directions. However, Elhajj et al. [19] found an influence of physical direction on JND for forces exerted in the horizontal plane in a discrimination experiment. Stimuli at every degree in the horizontal plane away from the subject were used. Afterwards, three regions of 60° each were defined. For each region, the percent-correct value was calculated. This showed that the medial region had a higher percentage of correctly discriminated trials than the left and right lateral regions.

One way to investigate the *relation between physical and perceived force direction* is by performing a matching task. Toffin et al. [20] are the only ones who have performed such an experiment. In their study, subjects had to reproduce a perceived force direction in the horizontal plane by moving a joystick, thus performing a perception task directly followed by a motor task. Different reproduction-errors for different directions were found, indicating an anisotropy in the reproduction of force direction. They did not report specific values for the different directions, but only tested the anisotropy as a whole. Moreover, their setup did not only test perception, but also motor performance as a response to perception. When there is a mismatch between the direction in which a force is exerted and the perceived direction, this mismatch could also be present in the perception of the reproduced force direction. This would result in two opposite errors that cancel out each other, so no error will be found. Therefore, it would be very useful to perform an experiment that involves only perception without a consecutive motor task to establish whether also in that case there is an anisotropy in the perception of force direction.

From the studies described, it is clear that literature on force perception in any direction other than the direction of gravity is limited and work on the relationship between physical forces and perceived forces in different directions is even more scarce. The aim of our study was therefore to investigate the perception of both magnitude and direction of forces at various non-cardinal directions in the horizontal plane, using a paradigm involving force magnitude estimation and force direction matching. Force magnitudes that are small enough to be used by operators in daily practice were used. Our study provides more insight into which direction and magnitude of forces humans are actually perceiving, rather than which differences they are able to perceive. It also shows if anisotropies, suggested by [9], [20] and in line with the illusion in [15], are present in the haptic perception of force. This could eventually aid in the design of haptic devices with more intuitive force feedback.

2 MATERIALS AND METHODS

2.1 Subjects

Ten right-handed (assessed using the Coren-test for handedness [21]), naive subjects participated in this study, 4 male and 6 female, aged 22±3 years (mean±standard deviation), height 1.78±0.08 m, with no known neurological disorders. All subjects gave written informed consent, received a compensation of 10 euros per hour and prior to the experiment were given written instructions on how to perform it. One additional subject had to be excluded from the analysis, because she was not able to perform the task correctly.

2.2 Setup

Subjects were seated on a height-adjustable chair (Figure 1). Vision was blocked by a computer screen in front of the subject's eyes, enclosed in a tent-like structure that prevented visual cues from the side. The subject's elbow was put in a sling, attached to the test frame. The height

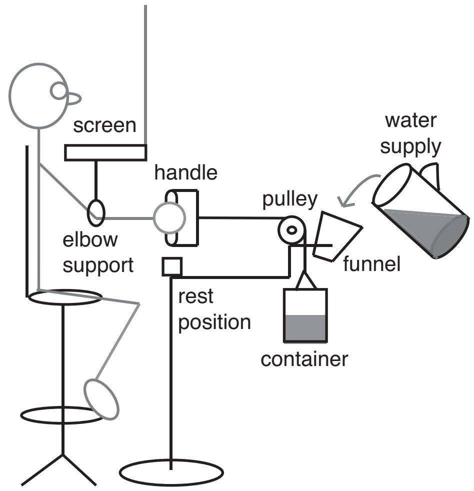


Fig. 1. Overview of the setup. To exert a force on the handle, water was poured in the container through the funnel. The whole setup was turnable around the vertical axis to create different force directions in the horizontal plane. Joint angles were fixed by restraining the elbow in a sling, which was connected to the test frame. Hand position was controlled by letting subjects place the handle at the rest position between trials, to ensure every trial started with the same hand position.

of the chair and the distance between the chair and the setup was adjusted so that the arm posture was the same for every subject. By measuring the angles between the limbs, a vertical angle of 75° between torso and upper arm, and an angle of 130° between upper and lower arm was ensured for all subjects (see Figure 2 for a top view of the subject's position). These joint angles provided a comfortable posture, mimicking the posture of operators using a master device in real situations. In the resting phase between all trials, subjects placed the handle at the position indicated with 'rest position' in Figure 1. The next trial started by letting the subjects lift the handle vertically, to ensure that all subjects performed the task using similar arm postures.

Subjects were asked to hold a handle on which a force could be exerted in the horizontal plane. The handle was connected to a container with a rope guided over a pulley. The stimulus force was increased gradually by pouring water in the container via a funnel, creating a force-ramp that ended at a certain plateau-force when all the water had reached the container. The steepness of the force-ramp was controlled by changing the size of the opening of the funnel. To exert force in different directions, the complete pulley-funnel system was turnable. The handle also had a turnable inside that could rotate independent from the outside of the handle, to allow changing the direction of the setup without the subject noticing in which direction the setup was turning.

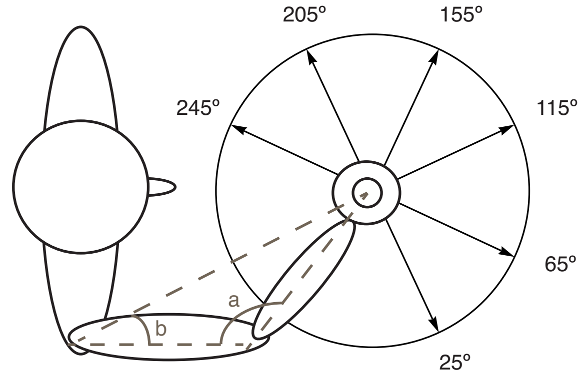


Fig. 2. Top view of the setup with used force directions for the right hand. For the left hand, mirrored directions were used. a: Angle between the upper and lower arm, set to 130° for all subjects; b: Angle between the line connecting shoulder and hand and the dorso-ventral axis of subject. This angle was roughly 25°.

2.3 Experimental procedure

During every trial, the force on the handle was gradually increased to a certain force-plateau through a force-ramp. By adjusting the funnel diameter, the force-ramp lasted five seconds for all force magnitudes. Subjects were wearing ear protectors with ear phones throughout the experiment. During the force-ramp, white noise was played to mask the sound of the water. Subjects were free to choose how long they wanted to perceive the plateau-force before answering, generally resulting in a few seconds of plateau-force exposure. The subject's task was to answer two questions about his/her perception of the force at this plateau-level, indicating the direction and the magnitude of the perceived force. Perceived direction was indicated by turning an arrow on a computer screen, placed in the horizontal plane beneath the subject's face. The arrow was manipulated using a computer mouse in his/her free hand by either pointing and clicking on the screen or by dragging the needle to the desired position. When the subjects were satisfied with their answer, they pressed an 'ok'-button to confirm their response[1]. Magnitude perception was indicated verbally through free magnitude estimation. No magnitude reference or range was provided.

Six directions covering three-quarters of the horizontal plane (245, 205, 155, 115, 65 and 25°, see Figure 2 for an overview of these directions) and five magnitudes (2, 3, 4, 5 and 6 N) were tested, resulting in 30 combinations for each hand. All direction-magnitude combinations were tested six times: three times while subjects held the handle with their right hand and three times with their left hand. The experiment was divided into three one-hour test sessions per subject. At each session, all

1. We are aware that this matching procedure could be influenced by visual distortion. However, there is no method that guarantees a bias-free measurement of these parameters.

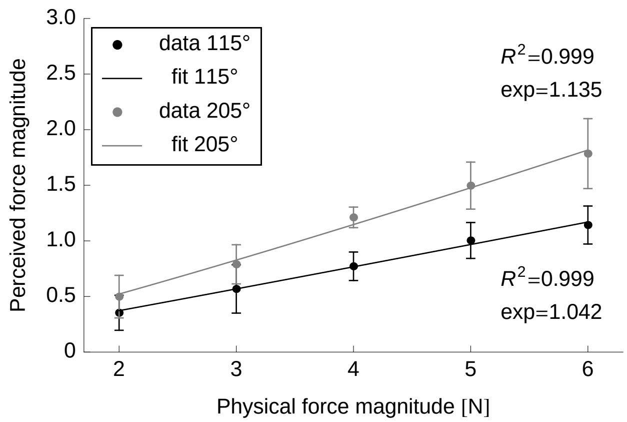


Fig. 3. Scaling of mean force magnitude perception data of all subjects as a function of physical force magnitude. The black dots show the magnitude data of the 115° direction, the grey dots show the data of the 205° direction, and error bars indicate standard deviations. A power function was fitted to the data (the solid black and grey lines). The fit showed a very high correlation with the data and its exponent did not differ from 1, which indicates a linear relationship. For clarity, only two of the six curves are shown. Note the difference in slope between the two lines, indicating a difference in force magnitude perception between the two directions.

TABLE 1
Exponents of all power functions, fitted to the magnitude perception data per subject per physical direction. The last two rows show the exponents and the coefficients of determination, R^2, of the power functions fitted to the data of all subjects.

subject	25°	65°	115°	155°	205°	245°
1	1.09	0.97	1.37	1.44	1.05	1.05
2	0.96	1.06	0.93	0.96	1.02	0.86
3	0.89	1.05	0.92	1.52	1.08	1.16
4	0.78	0.64	0.75	0.75	0.78	0.80
5	0.88	0.84	1.50	1.02	0.99	1.27
6	0.87	1.07	1.00	1.04	1.21	1.17
7	1.35	1.00	0.87	1.18	1.35	1.27
8	1.10	1.24	1.29	1.62	1.30	1.30
9	1.73	1.97	2.40	3.23	2.05	2.29
10	0.39	0.46	0.25	0.42	0.41	0.38
all	1.02	1.03	1.04	1.17	1.14	1.13
R^2 all	0.9991	0.9986	0.9993	0.9997	0.9990	0.9997

30 direction-magnitude combinations were tested once on both, resulting in a total of 180 trials per subject. The hand-order was counterbalanced and the direction-magnitude combinations were presented in a randomized order that was different for every session. Every session started with three practice trials to familiarize the subjects with the task. If the subjects did not perform the task correctly, they were given feedback to adjust their procedure. Generally, this was only needed during the practice trials. Subjects did not receive feedback about the responses they gave.

2.4 Data analysis

Coordinates of the left-hand trials were mirrored before analysis to ensure that the same coordinates represented the same directions with respect to the subject's hand in both data sets, i.e. all data were represented in right-hand coordinates. Perceived force directions were directly compared to physical force directions.

Literature on magnitude perception in the direction of gravity reported power functions with different exponents for the relation between physical and perceived magnitude [11]. Since this exponent is needed to choose the proper normalization method, a power function was fitted to our magnitude perception data at the different levels of physical force magnitude. This was done for every physical direction separately, for the individual values (used in the statistical analysis) and for the data of all subjects together (Figure 3 and Table 1). At one of the angles the exponents were not normally distributed over the subjects (Shapiro-Wilkinson test, D_{10}=0.82, p=0.028), so a non-parametric test was used to assess the medians of the exponents based on the individual fits. As the fits did not differ from a linear fit, as will be described in more detail in the results section, a simple normalization method could be used. This normalization was done by dividing the perception data by the actual force magnitude, resulting in values that represented the ratio between perception and actual force magnitudes. From these ratio values, the mean was calculated per subject per session. The ratios were then scaled to have a mean of one, by dividing the ratio values by the mean, per subject and session. This resulted in ratios that all had a mean of one per subject and session, but which still represented the distribution of values before normalization and scaling. After this, an outlier analysis was performed on both the normalized magnitude and the direction data per subject. This resulted in a maximum number of nine outliers per subject (maximally 5% of the subject's data set, but for most subjects about 2%). Means of all magnitude-direction combinations were calculated by averaging the data from the three sessions.

2.5 Statistics

The effects of physical force direction, physical force magnitude and used hand on the errors in direction and on the normalized magnitude values were analyzed with a repeated measures ANOVA. When the sphericity-criterion was not met, Greenhouse-Geisser correction was used to adjust the number of degrees of freedom. To assess if the medians of the errors in direction were different from zero, a non-parameteric Kruskal-Wallis test per subject per physical angle was performed, as

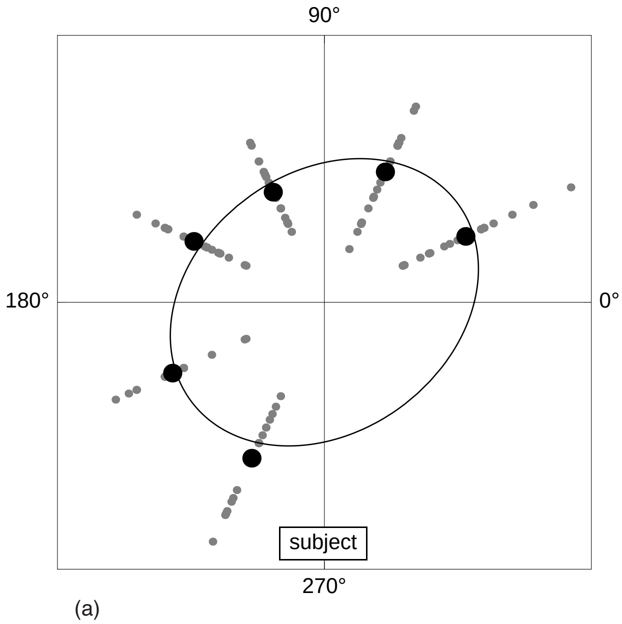


Fig. 4. Magnitude perception data with fitted ellipses, showing a polar view of the magnitude perception data at different physical directions. The greater the distance from the centre of the graph, the higher the perceived magnitude was. Data from the left-hand trials were mirrored before averaging over hands. The subject was sitting at the marked position. (a) Data of one typical subject. Grey small dots represent individual trials, while the large black dots show the mean magnitude perception values in that direction. An ellipse was fitted through these data, shown in black. Note that although the spread of the data is quite large, the general elliptical shape of the data is very apparent. (b) Ellipses fitted to normalized magnitude perception data for the individual subjects (grey) and the mean fit for the complete data set (black).

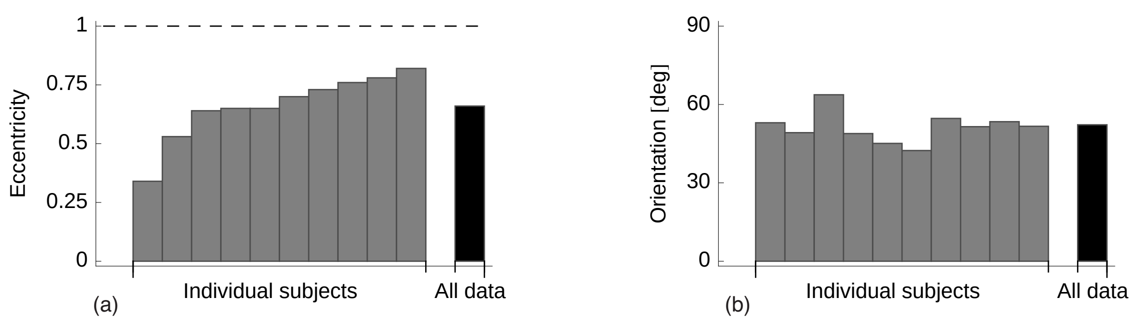


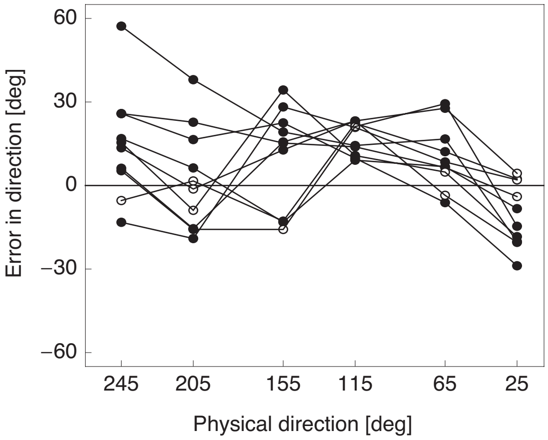
Fig. 5. Parameters of ellipse fit, for the individual subjects (grey) and for the fit to the complete data set (black). (a) Eccentricity of the fitted ellipses. The dotted line indicates the value 1, which would be a perfect circle. (b) Orientation of the major axis of the fitted ellipses. Note that especially the ellipse orientation varies very little between subjects.

the individual data per angle were not normally distributed (Kolmogorov-Smirnov test, $D_{252}\leq 0.13$, $p\leq 0.022$, for all physical directions). An ellipse was fitted to the normalized magnitude data per subject and for all the data together. The mean eccentricity of the ellipses was tested using a one-sided one-sample t-test, as these parameters were normally distributed (Shapiro-Wilkinson test, D_{10}=0.86, p=0.15). Eccentricity values cannot exceed the value one, therefore a one-sided test was used. The consistency of the error patterns for force direction was assessed using Pearson's correlation coefficient r, along with its significance. Correlations were calculated per subject by comparing the error patterns of the different force magnitudes, hands and sessions.

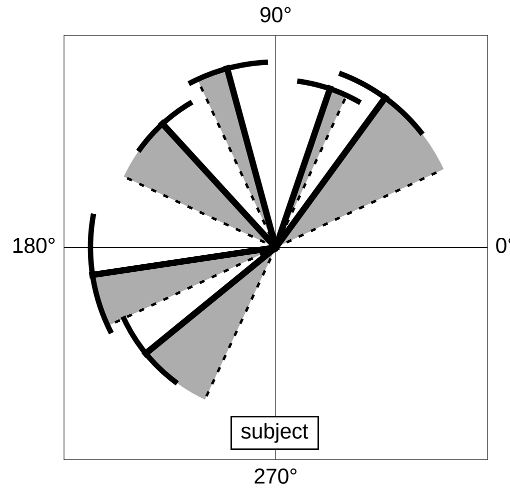
3 Results

3.1 Force magnitude

Scaling of force magnitude perception was tested by fitting a power function to the data. A Wilcoxon Signed Rank test showed for all directions that the median of the exponents did not differ significantly from 1



(a)



(b)

Fig. 6. Difference between the physical and perceived force directions. Data from the left-hand trials were mirrored before averaging over hands. (a) Errors made by the subjects, ranging from the palmar side of the hand (left part of the graph) to the dorsal side of the hand (right part of the graph). Each dot represents the error of one subject at that physical direction and each line connects all errors of one subject. Filled (open) dots show physical directions at which the subject made an error that was (not) significantly different from zero. The range of errors was large and the shape of the error patterns differed between subjects. (b) Alternative representation of an error pattern of one subject, shown in a top view of the set-up, with the subject sitting at the marked position. Dotted lines represent physical angles, solid lines represent perceived angles, shaded areas show the difference between these two (i.e. the error subjects made) and arcs show the standard deviation. Reading the graph in (a) from left to right is congruent to reading the graph in (b) in a clockwise direction.

($0.24 \leq p \leq 0.88$), so the scaling of force magnitude data did not differ from linear. In Figure 3 and Table 1, the relation between physical and perceived force and the fit is plotted, showing that the ratio of physical to perceived force was constant over the force range. Repeated measures ANOVA on normalized magnitude values showed a significant effect of physical angle ($F_{2.3,20}$=19, p<0.01), but no effect of physical force magnitude ($F_{1.1,9.6}$=1.1, p=0.32) or used hand ($F_{1,9}$= 0.39, p=0.55). Consequently, the data set for magnitude could be merged for hand and physical force magnitude. When the normalized magnitude data were plotted in a polar plot, the data resembled an elliptical pattern (Figure 4a). Ellipses were fitted to the data for every subject and to the complete data set of all subjects together (Figure 4b), which fitted the data quite well. This can be seen from the coefficient of determination, R^2, which ranged between 0.82 and 0.95 for the individual fits. Data of one subject had a somewhat poorer fit of 0.61. The coefficient of determination for the fit to the complete data set was 0.86. The eccentricity of the ellipses was significantly smaller than 1 (one-sided one-sample t-test: t_9=-7.6, p<0.01), meaning that the fitted figure is an ellipse and not a circle (Figure 5a). The orientation of the ellipses was very similar over subjects (Figure 5b). The eccentricity of the ellipse fitted to the complete data set was 0.66 and the orientation of its major axis was 52°.

3.2 Force direction

From the repeated measures ANOVA of the differences between physical and perceived direction (see Figure 6 for an overview of all force direction data), it appeared that there was only an effect of physical angle ($F_{2.4,22}$=4.5, p=0.018) and none of physical force magnitude ($F_{2.0,18}$=1.4, p=0.27) or used hand ($F_{1,9}$=0.24, p=0.64). Therefore, the direction data set was merged for hand and physical force magnitude. A Kruskal-Wallis test showed that all subjects made significant errors at various physical directions. In Figure 6a, the filled dots indicate these significant differences, showing that errors differed from zero for 48 of the 60 subject-direction combinations. There was, however, a large range in errors between subjects. Moreover, the error patterns did not have the same shape, which is clear from the lines connecting the errors per subject in Figure 6a. An alternative representation of an error pattern is given in Figure 6b, by showing the errors of a subject in a top view of the set-up. Although the patterns were not consistent between subjects, the consistency of the error patterns within subjects was quite strong, as illustrated in Figure 7. This figure illustrates the general trend that within the data of one subject, the same patterns arise when the errors in direction are compared between the different force magnitudes, hands and sessions. Correlation analysis of these comparisons per subject confirmed

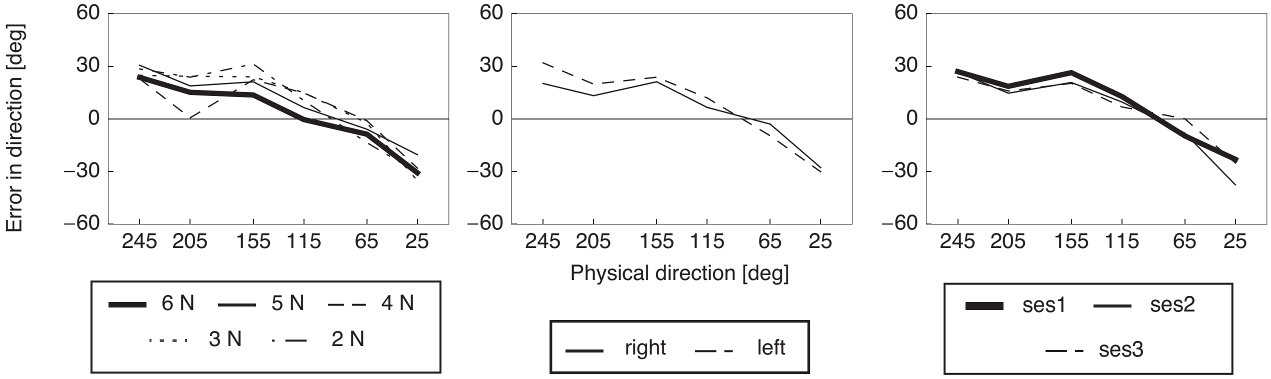


Fig. 7. Illustration of the within-subject consistency of errors in direction perception, using data of one typical subject. Left: error pattern per physical force magnitude, with one line per magnitude. Middle: error pattern per used hand, with one line per hand. Right: error pattern per session, with one line per session. All sessions were measured on different days, which makes this an indicator of the repeatability of the measurements over time. The error patterns are consistent over physical force magnitudes, used hand and measurement days.

that the patterns were quite consistent, as 53 of the 100 magnitude correlations, 5 of the 10 hand correlations, and 23 of the 30 session correlations were significant. The median value of the coefficients was 0.84 for the force magnitudes, 0.85 for the hands and 0.92 for the sessions.

4 Discussion

Since for both the perception of force magnitude and the perception of force direction a significant effect of physical force direction was found, force perception in the horizontal plane is anisotropic. This is an important finding with regard to applications of haptic force perception, such as haptic force-feedback control systems. Of course, it is also an interesting finding in a more fundamental sense.

4.1 Force magnitude

Scaling of force magnitude did not differ from linear for the magnitude range in this study, so the ratio of perceived to physical magnitude was constant. This agrees with results of a study in which the scaling of force, ranging between 0.15 and 0.70 N and applied normally and tangentially to the index finger, was linear for both force directions [22]. Earlier studies on force magnitude scaling have mainly used forces in the direction of gravity or magnitudes that were much higher. In these studies, power functions with exponents varying between 0.7 and 2.0 were found [11], [14], so our data fit in that range. No influence of physical force magnitude was found, so the different force magnitudes did not cause significantly different normalized force magnitude perception patterns.

The pattern of normalized force magnitude data in a polar plot showed a remarkably similar-oriented elliptical pattern for all subjects (see Figure 4b). The minor axis of the ellipse was always oriented roughly in the same direction as the arm (Figure 5b). This indicates that subjects perceived a force as larger when it was exerted perpendicular to the arm, than when it was exerted along the arm. The observed pattern makes sense intuitively, as you would expect that resisting a force in line with the arm is easier than resisting one perpendicular to the arm. Nonetheless, it is intriguing that it is apparently not only easier to do, but is also perceived as a lower force magnitude. The way in which an arm reacts to external disturbances can be described using arm impedance characteristics [23]. For small displacements and without voluntary muscle control, the following equation describes arm impedance:

$$\boldsymbol{M}\ddot{\mathbf{x}}(t) + \boldsymbol{B}\dot{\mathbf{x}}(t) + \boldsymbol{K}\mathbf{x}(t) = \mathbf{f}(t) \tag{1}$$

in which $\boldsymbol{M}$, $\boldsymbol{B}$ and $\boldsymbol{K}$ indicate the matrices of inertia, viscosity and stiffness, respectively, and $\mathbf{f}$ indicates the force driving the arm to move.

All of these parameters are anisotropic for the human arm (e.g. [24]) and can be represented with an ellipse, which suggests a connection with our perception data. The shape and orientation of these ellipses depend on many factors, among which arm position is very important [25], [26]. In our study, we tried to ensure that all subjects used the same posture. The chair could not turn, elbow position was fixed, the start position of the hand was the same in every trial and the subjects were instructed to keep their hand at the same place during the trials. However, we did not measure arm position directly, so we cannot calculate the absolute contribution of the different parameters. Nonetheless, we can make an educated guess about their relative contribution, based on qualitative analysis of the parameters. Artemiadis et al. [27] asked subjects to keep their hand steady while a dynamic force profile was applied and found that the stiffness ellipse ($\boldsymbol{K}$) was magnitudes larger than the viscosity ($\boldsymbol{B}$) and inertia ($\boldsymbol{M}$) ellipse. In our study, the task was also to keep the hand steady. Some horizontal motion ($\mathbf{x}$) was observed during the trials, but the displacement was a few centimeters maximally, as the setup did not allow for larger movements. If movement was observed, this happened very slowly, because the force ($\mathbf{f}$) was added gradually. Consequently, the velocity ($\dot{\mathbf{x}}$) and acceleration ($\ddot{\mathbf{x}}$) values were probably relatively small. Taken together, it seems unlikely that the products $\boldsymbol{M}\ddot{\mathbf{x}}$ and $\boldsymbol{B}\dot{\mathbf{x}}$ played a large role in the total arm impedance, making stiffness the most likely governing arm impedance parameter in our study.

For tasks avoiding voluntary muscle control and performed with the arm in the horizontal plane, the arm stiffness ellipse is oriented along the line between hand and shoulder [28], [23], [29], [30], [31]. When voluntary muscle control is present, as was the case in our study, it can change the size and the eccentricity of the stiffness ellipse [25] and its orientation [32], [33], [25], [26]. However, Krutky et al. [34] show that the orientation of the ellipse does not change in a task where subjects have to maintain a posture, while an external disturbance is presented, which was also done in our study. Consequently, the orientation of the stiffness ellipse measured without voluntary muscle force will be good enough as a rough estimation of the orientation of the stiffness ellipse in our study, even though voluntary muscle control was present. To provide a natural posture for task execution, the arm of our subjects was not positioned in the horizontal plane. One other study investigating arm stiffness outside of the horizontal plane used a posture with the elbow below the shoulder and hand [35]. The shoulder and hand were both positioned in the horizontal plane. In this posture, the major axis of the arm stiffness ellipse was still oriented from hand to shoulder in the horizontal projection. Therefore, we assume that maximum arm stiffness for the posture in our study was also oriented along the hand-shoulder line.

A link between arm impedance and motor behaviour was found by showing that arm stiffness ellipses were correlated to the very consistent elliptical anisotropy in forces exerted by subjects in a motor task [36]. In our study, magnitude perception of the different subjects also showed a very consistent elliptical anisotropy. The exact orientation of the hand-shoulder line, and thus of the hypothesized major axis of the stiffness ellipse, was not documented in our study, but we estimated the orientation to be 25° on average, based on measurements of arm length, elbow angle and setup configuration (see Figure 2 for this hand-shoulder line). In Figure 8 both the fitted mean magnitude perception ellipse and the estimated hand-shoulder line are shown. The major axis of the arm stiffness ellipse from Mussa-Ivaldi et al. [30] with a posture most similar to the posture in our study is also shown. From Figure 8 it is clear that the orientation of the hand-shoulder line in our study and the stiffness data from literature [30] show a remarkable similarity to our measured force magnitude data. So, both our educated guess and the general features of arm stiffness suggest this parameter could be the governing one.

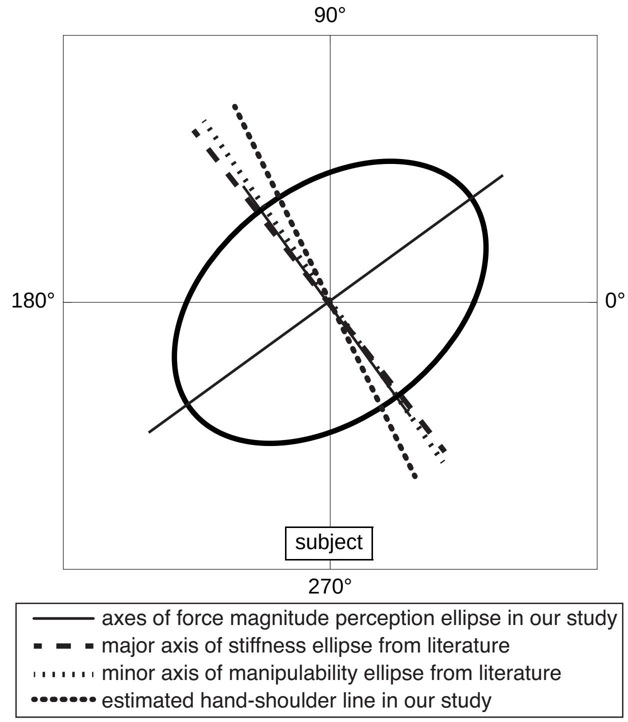


Fig. 8. Possible explanation for ellipses found for force magnitude perception. The fitted mean force magnitude ellipse to our complete data set is shown, with its major and minor axis as a solid line and the position of the subject marked. The thick dashed line indicates the major axis of the arm stiffness ellipse found in [30] (hand-shoulder angle 35°), the thin dashed line indicates the arm manipulability ellipse found in [14] (hand-shoulder angle 35°) and the dotted line indicates the estimated orientation of the line between hand and shoulder in our study (roughly 25°). All the segmented lines are very similar to the orientation of the minor axis of the force magnitude perception ellipse found in our study, so both stiffness and manipulability could be related to force magnitude perception.

Our force perception results fit nicely with a study by Tanaka et al. [14], who looked at force magnitude perception at larger magnitudes. They also found elliptical force perception patterns, oriented roughly in the same direction as our ellipses. Their explanation for the perception anisotropy is based on another arm characteristic, which is arm manipulability. Arm manipulability refers to the ease with which an external force can displace an arm, either robotic or human, in a certain direction, based on arm configuration and the range of possible joint velocities or torques [37], [24], [27]. Tanaka et al. [14] argue that the ellipses they find for force perception are very similar to the manipulability ellipses of the human arm. The minor axes of the manipulability ellipses in their study are oriented along the line between hand and shoulder. So, both the stiffness ellipse and the manipulability ellipse point roughly from hand to shoulder, as can been seen in Figure 8. They both show a remarkable similarity to the force perception patterns we found and both give a measure of the ease of force production in a certain direction. So, regardless of which parameter is the main factor, the results suggest that static force magnitude perception in the horizontal plane is governed by the ease with which the force is resisted rather than the actual force magnitude.

This agrees with theories in literature, stating that humans possess a 'sense of effort', describing the sense of ease of force production. This term was introduced by McCloskey et al., when they found that subjects who fatigued their reference arm by keeping a weight lifted, chose higher matching weights over time. The matching weights were held for a short period, which avoided fatigue in the matching arm [38]. The same effect is observed when forces are perceived with locally anesthesized hands or when forces are perceived by patients with particular neuromuscular disorders (e.g. [39]). All these studies show that even when the force does not change, the perception of force does change according to the amount of effort subjects experience. This 'sense of effort' is probably related to kinaesthetic perception rather than tactual perception, as it is related to arm mechanics. However, we cannot conclude this from our experiment, as a combination of kinaesthetic and tactile cues was present.

It is interesting that humans, who have been perceiving forces all their life, are not able to correct for the anisotropic nature of effort in order to obtain a correct sense of force. It is probably more instructive to have information about effort rather than absolute force, as effort represents the ease with which one will be able to perform a task. However, when force is used to communicate information, as in a haptic device, it might be better to scale the force magnitude according to its direction to produce an isotropic sense of effort.

4.2 Force direction

Significant distortions in perception of force direction were found for all subjects. No influence of physical force magnitude was found, so the different force magnitudes did not cause significantly different force direction errors. Within subjects the patterns were quite consistent (Figure 7 and the correlation analysis), but between subjects, large differences were found (Figures 6a and 6b). As the mean errors in direction were significantly different from zero for multiple physical directions for all subjects, these errors are not just random variations, but indications of actual distortions. The presence of an effect of physical force direction on the error in perception shows that this distortion is not a simple rotation of the complete system, but differs per physical direction. If the errors were related to arm mechanics, all subjects would show a similar pattern, as their arm postures were similar. This is not the case, so stiffness or manipulability cannot be used to explain the variation found between subjects. More research is needed to answer this question. Nonetheless, the consistency of the patterns within subjects could already be useful in the design of force-feedback, by using the pattern particular to that operator to adjust the direction of the forces that are fed back.

Lastly, no effect of used hand on the perception of force direction or magnitude was found, even though all participants were right-handed, indicating that the ability to haptically perceive force is not trained by using hands more often or for more precise tasks. The dominant hand did not yield lower magnitude perception values. Probably, this happened because the trials with the same hand were presented in a block at every session. This allowed for a re-scaling of the perception data to the experienced force range when switching to the other hand half-way the session.

5 Conclusion

Both the perception of force direction and magnitude was anisotropic in the horizontal plane. Perception of force direction was significantly distorted at various physical directions for all subjects. Between subjects, the patterns of these errors varied. Within subjects, the patterns were quite consistent. Distortion of force magnitude showed an elliptical pattern that was very comparable between subjects. All subjects perceived forces exerted along the line between shoulder and arm to be smaller than forces exerted perpendicular to this line. The force magnitude ellipses were oriented roughly perpendicular to arm stiffness and similar to the arm manipulability ellipses found previously, meaning that forces perceived in a direction with higher arm stiffness and lower manipulability are perceived as being smaller. Humans thus seem to possess a 'sense of effort' rather than a 'sense of force', which might be more helpful in performing tasks of everyday life. Both the distortion in direction and magnitude of force perception are interesting phenomena that could be important for the design of haptic devices.

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